Glacial Sediment Stores and Their Reworking

Porter, Philip R.; Smart, Martin; Irvine-Fynn, Tristram

Published in:
Geomorphology of Proglacial Systems

DOI:
10.1007/978-3-319-94184-4_10

Publication date:
2019

Citation for published version (APA):
Porter, P. R., Smart, M., & Irvine-Fynn, T. (2019). Glacial Sediment Stores and Their Reworking. In T. Heckmann, & D. Morche (Eds.), *Geomorphology of Proglacial Systems: Landform and Sediment Dynamics in Recently Deglaciated Alpine Landscapes* (pp. 157-176). (Geography of the Physical Environment). Springer Nature. https://doi.org/10.1007/978-3-319-94184-4_10

4 HILLSLOPE PROCESSES IN THE PROGLACIAL ZONE

4.1 GLACIAL SEDIMENT STORES AND THEIR RE-WORKING

INTRODUCTION

Understanding the storage and flux of sediments through the proglacial zone of deglaciating catchments is an important topic within glacial geomorphology, primarily as there is great uncertainty surrounding the timescales that sediments are stored and released, which has implications for fully understanding landform genesis and the response of landforms and glaciated catchments to current and forecast environmental changes. The steep slopes found in alpine glacial environments, combined with associated potential for intense geomorphological activity, offer favourable conditions for the release, reworking and storage of glacial sediments and play an important part in the geomorphic coupling and overall connectivity of the down-valley sediment cascade (Cavalli *et al*., 2013; Heckmann and Schwanghart, 2013; Carrivick and Heckmann, 2017; chapter 6.2). It is no surprise, therefore, that processes acting on hillslopes have formed the focus for much research investigating the sedimentary response to deglaciation.

The concept of a so-called ‘paraglacial period’ of enhanced geomorphological activity conditioned by glaciation (or indeed deglaciation) originally detailed by Church and Ryder (1972) and subsequently developed by several authors, most notably Ballantyne (2002a), has received much attention in recent years, as the geomorphological consequences of deglaciation become ever more apparent. Hillslopes and associated slope processes in glaciated regions are likely to play a key role in that heightened geomorphological activity and associated release, reworking and subsequent redeposition, or storage, of glacial sediments. However, any sedimentary or ‘paraglacial’, response to deglaciation is complex and different landsystems will respond at differing rates and on differing spatial scales (Ballantyne, 2002b) and this is certainly the case with hillslopes, which can both store and release sediments at the catchment scale, with potentially significant spatial and temporal variability in both storage and release. Hillslopes in deglaciating environments also demonstrate the attributes of both primary and secondary paraglacial systems. Primary paraglacial systems are those where sediment release is directly conditioned by glaciation (e.g. sediment-mantled slopes) while secondary paraglacial systems are those where rates of sediment release are additionally controlled by reworking of paraglacial sediment stores (e.g. debris cones and fans at the base of drift-mantled slopes. Ballantye, 2002b). The presence, operation and interaction of these primary and secondary systems inevitably add complexity to the deglaciation response.

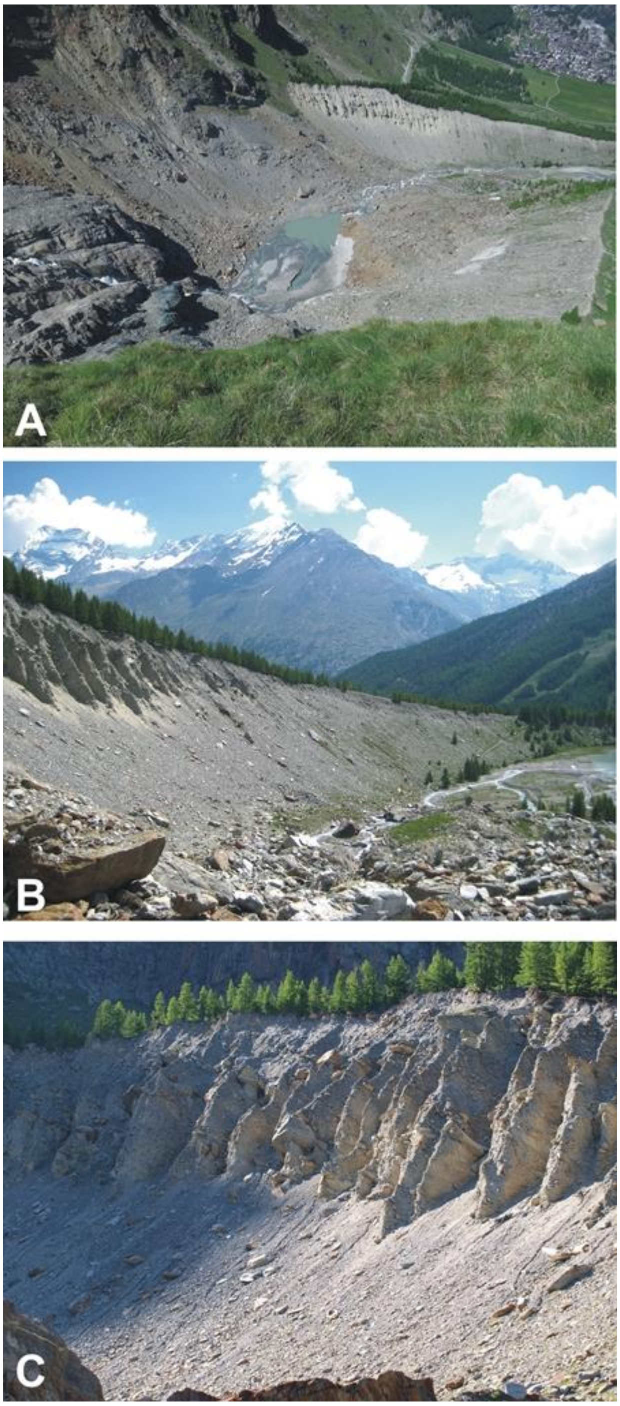
Direct glacial influence on sediment release and reworking is likely to decrease as distance down valley increases, but smaller glaciers have been observed to play an important role in efficiently coupling slope and fluvial processes (e.g. Lukas *et al*., 2005), ensuring that sediment fluxes from glaciated alpine catchments are dominated by fluvial processes (e.g. Orwin *et al*., 2010; Carrivick *et al*., 2013). However, critical to that fluvial reworking and redistribution is the supply of sediments from adjacent slope units and the degree of connectivity between slope and fluvial systems, both of which will also vary in space and time (e.g. Cavalli *et al*., 2013; Heckmann and Schwanghart, 2013; Lane *et al*., 2017; chapter 6.2). Potential supply limitation from those slope units to fluvial systems therefore becomes an important parameter partially dictating the extent to which fluvial systems act as an effective mechanism of sediment redistribution into the down-valley sediment cascade (Cavalli *et al*., 2013). Processes acting upon hillslopes and associated storage, release and reworking of sediments in the hillslope domain therefore play a significant role in controlling the basin-scale flux and yield of sediments during deglaciation.

It could be argued however, that in comparison with the wealth of research conducted in high-latitude environments, investigation of the paraglacial response to deglaciation in alpine environments is relatively under-studied. This is perhaps unsurprising, given the very obvious and dynamic geomorphological activity and landscape modification associated with processes of thermo-erosion and mass movement at high latitudes (e.g. Etzelmüller, 2000; Lyså, and Lønne, 2001; Irvine-Fynn *et al*., 2005; Porter *et al*., 2010; Irvine-Fynn *et al*., 2011; Ewertowski and Tomczyka, 2015). In comparison, many deglaciating alpine environments, at least superficially, appear to exhibit relative stability following Little Ice Age glacier retreat and subsequent stabilisation of many proglacial areas through, for example, relatively undisturbed vegetation colonisation well beyond pioneer stages (e.g. Eichel *et al*., 2013; Eichel *et al*., 2015). However, as deglaciation gathers pace in alpine regions (e.g. Barry, 2006, Radić and Hock, 2011; Klaar *et al*., 2015), the requirement for a fuller understanding of sediment fluxes becomes enhanced, both due to a need to understand the complex geomorphological and sedimentological responses to deglaciation and to assess any potential impacts on, or from, human activities in alpine areas (e.g. Moore *et al*., 2009; Otto *et al*., 2009; Carrivick *et al*., 2013).

OVERVIEW

Perhaps the most visually obvious manifestation of hillslope glaciogenic sediment storage, release and redistribution within deglaciating alpine environments are the large, often dissected, lateral moraines that flank many systems throughout alpine regions (e.g. Curry *et al*., 2005; Curry, *et al*., 2009; Lukas *et al*., 2012, Figure 1). Although perhaps less visually obvious, the extensive suites of sedimentary ice-marginal landforms and features found in proglacial zones also represent an important store and source of glacial and related sediments associated with deglaciation, likely subject to extensive sediment redistribution and re-working that may lead to both modification of landscape morphology and impacts on sediment fluxes through the down-valley cascade during deglaciation.

In this chapter we therefore consider storage within, and supply of sediments from, slopes within ice-marginal and proglacial environments. Inevitably however, there is the potential for overlap with the content of other contributions in this volume, as hillslopes represent a fundamental and pivotal connection between geomorphic systems, controlling both the supply and storage of sediments and being subject to the full range of geomorphological processes. We therefore limit our consideration to landforms in the proglacial zone, as these features not only represent sizeable and important stores of glaciogenic and other sediments, but represent a highly dynamic geomorphological environment that impacts upon and interacts with the multiple geomorphic and biogeomorphic systems within the basin sediment cascade that are considered elsewhere in this volume.



103

Figure 1. *Deglaciating proglacial alpine landscapes, Feegletscher Nord, Valais Switzerland. A. Aerial view showing recent rockfall and slope debris to the left of the image, proglacial lake dammed by moraines and rockfall debris and heavily dissected lateral moraine sequence to the top right of the image. B. Proximal face of lateral moraines showing extensive dissection and gullying, with debris cone build-up progressively burying slope units with increasing distance from the glacier snout (out of shot behind the photographer). C. Gullied lateral moraine slopes showing distal dipping fabric and slope foot debris accumulation. Note the mature vegetation at the slope crest, which extends down the distal slope away from the camera.*

Although subglacial and supraglacial sediments also represent an important source from which the sediments contained within ice-marginal landforms and features may ultimately be derived (Barr and Lovell, 2014), these systems and sediments are considered in sections 3.3 and 3.4 respectively and are therefore not discussed in detail here. Similarly, the reduction in lateral slope support associated with deglaciation, known as debuttressing, is likely to enhance the likelihood of rockfall activity (e.g. Stoffel *et al*., 2014; Vehling *et al*., 2016) and associated delivery of predominantly larger calibre sedimentary debris to moraine sequences (e.g. Shulmeister *et al*., 2009; Cossart *et al*., 2008; Reznichenko *et al*., 2011), while periglacial systems such as rock glaciers also represent an effective store and potential source of slope sediments (Stoffel and Huggel, 2012; Müller *et al*., 2014) that may be subsequently reworked. Rockfall activity however is discussed in detail in section 4.1, while rock glaciers are considered in section 3.5.

Therefore, rather than considering the broader scale catastrophic and/or slow mass movements which may arise as a result of the same climatic forcing that drives deglaciation and contribute additional sediments for paraglacial reworking and redistribution, here we limit our consideration to those sedimentary slope units directly related to glacial activity and subject to paraglacial modification. These comprise lateral and forefield glacial and glaciofluvial sedimentary landforms, their component slope units and processes operating thereon.

LATERAL SLOPES

Formation and fluxes

Although large suites of lateral moraines commonly exhibiting numerous, narrow, parallel ephemeral channels, hereafter referred to as gullies, are a characteristic of many deglaciating alpine systems (Figure 1), the details of lateral moraine formation and internal structure remain incompletely understood. This situation has arisen in part, due to moraine spatial location with respect to the contemporary glacier front and patterns of glacier fluctuation based thereon, being the focus for much research to date (Lukas and Sass, 2011; Lukas *et al*., 2012). Early theories of lateral moraine formation generally assumed that subaerial weathering and resultant erosion was primarily responsible for accumulation of sediment at the ice margin, with additional contribution of sediment from englacial sources (e.g. Eyles and Rogerson, 1978; Rothlisberger and Schneebeli, 1979; Eyles, 1983). Latter theories invoke processes of repeated 'stacking' of ice-derived debris flows at the glacier margins, with sedimentary stratification, gently sloping distal morphology and limited dating providing evidential support for such incremental formation (e.g. Small, 1983, 1987). However, substantial subglacial and glaciofluvial sediments observed within lateral moraines at Findelengletscher, Switzerland, contrast with observations made elsewhere and highlight the potential importance of sediment transfer via englacial pathways (Lukas *et al*., 2012), while work conducted in geomorphologically active alpine areas has highlighted the rapid rate at which rockfall debris may become incorporated in the englacial environment and advected towards the glacier margin for subsequent deposition (e.g. Dunning *et al*., 2015). More recent geophysical investigations indicate complex ice-marginal moraine depositional history and evidence of polygenesis (e.g. Midgley *et al*., 2013; Tonkin *et al*., 2017). These observations combined, highlight the potential genetic complexity of lateral moraine features. Irrespective of the precise modes of formation, it is clear that lateral moraine complexes represent a substantial store of glacial and/or glaciofluvial sediment (Otto *et al*., 2009) that has the potential to be extensively re-worked and re-distributed during deglaciation.

The extent to which any given slope unit will yield sediments which are then incorporated into the down-valley transfer of sediments, or sediment 'cascade', will depend on multiple factors, including, but not restricted to, slope geotechnical properties such as lithology and degree of consolidation (e.g. Curry *et al*., 2009; Lukas *et al*., 2012), topographic setting (e.g. Barr and Lovell, 2014) and the consequent nature and efficacy of geomorphological processes (e.g. Curry, 1999; Curry *et al*., 2006). These factors will clearly vary in space and time (Ballantyne, 2002b, Orwin and Smart 2004a) with the result that the detailed sedimentological consequences of paraglacial activity are uncertain (Curry and Ballantyne, 1999), with relatively few studies to date directed towards identifying a sedimentological signature associated with paraglacial reworking (e.g. Benn and Ballantyne, 2005; Curry *et al*., 2009). This uncertainty is in no small part due to the fact that a given slope unit can act as both a store and a source of sediment, with secondary paraglacial activity furthering the complexity of the landscape response. Lateral moraines represent an interesting example of this dual 'sink' and 'source' role. Being commonly located away from highly dynamic proglacial fluvial systems, lateral moraines are more usually dissected, reworked and modified on an episodic basis through the operation of debris flow activity, facilitated by, for example, extreme precipitation events, spring thaw (e.g. Blair, 1994; Kellerer-Pirklbauer *et al*., 2010) and thermo-erosion of dead ice bodies (e.g. Kjær & Krüger 2001; Schomaker & Kjær, 2008; Lukas *et al*., 2012).

Lateral slope stability

The extent to which any slope unit releases sediments for reworking into the down-valley sediment cascade will relate in part to the overall geomorphic stability of that unit. Lateral moraines may be particularly important in this respect, due to their ability in many cases to stand stably at extreme angles. Many lateral moraines exhibit very steep (>60°) proximal slopes that appear to retain stable form, despite ongoing paraglacial reworking (e.g. Curry *et al*., 2005; Curry *et al*., 2009) and are indicative of the storage of glaciogenic sediments in a quasi-stable state. Where moraines exist in such a steep, stable form, any role as a source of sediment is likely to become diminished. Slope stability, or lack thereof, then becomes an important determinant of the delivery and storage of sediments within a deglaciating environment, as enhanced paraglacial activity and associated sediment delivery from current or former ice-marginal areas is not an inevitable and immediate consequence of deglaciation where factors such as time, climatic setting and geotechnical properties may well induce long-term slope stability. The extent to which the stability of a given slope unit is compromised, such that the unit might act as a source of sediment, will be dictated by multiple factors. These may include processes such as de-buttressing and resultant gravitational deformation (e.g. Hugenholtz *et al.*, 2008), the action of fluvial processes, which may also be exacerbated by extreme events such as glacier lake drainage (e.g. Iturrizaga, 2008), antecedent saturation and soil suction levels (e.g. Springman *et al.*, 2003; Hürlimann *et al.*, 2012) and complex combinations and interactions of geomorphic processes, such as freeze-thaw, snowmelt, water infiltration and consequent sub-surface flow, seepage and outflow (Hürlimann *et al.*, 2012). Clearly therefore, detailed genesis and long term stability of moraines will be dictated by multiple elements, with glacial conditioning and local geomorphological factors being of particular importance (Hugenholtz *et al.*, 2008).

Given the likely complex genesis of lateral moraines, combined with relative uncertainty over their stability, preservation and reworking potential and formative mechanisms (Lukas *et al.*, 2012), they present something of a conundrum, having the potential to act as both a dynamic sediment source where paraglacial modification and reworking is taking place (e.g.

Irvine-Fynn *et al*., 2011) and a relative sediment sink where stability is evident (e.g. Otto *et al*., 2009, Blair, 1994).

The material properties and genetic mechanisms that permit some lateral moraines to stand stably at angles, that in some cases exceed 70° (e.g. Whalley, 1975; Lebourg *et al*., 2004; Curry *et al*., 2005; Lukas *et al.,* 2012), remain incompletely understood, although recent work conducted in the European Alps has highlighted the importance of processes such as overconsolidation (e.g. Lukas *et al*., 2012) and the steepness of underlying bedrock (Lukas, pers. comm.). This characteristic of many lateral moraines is important in the context of sedimentary deglaciation dynamics as, irrespective of the source of sediment (subglacial, englacial, glaciofluvial, subaerial) slope stability necessarily means that sediments are held in transient storage, but are also potentially available for release, re-working and subsequent re-deposition, as evidenced by the presence of gullies and associated slope-foot deposits (Figure 1B and C). This ability of steep lateral moraines to hold sediments in quasi-stable form has implications for the correct interpretation of paraglacial sediment dynamics. Models of paraglacial system behaviour (e.g. Church and Ryder, 1972; Matthews, 1992) often propose maximum sediment production at or soon after deglaciation, followed by a simple and continuous, uni-directional decline. However, transient storage in and stochastic release of sediments from sources such as quasi-stable lateral moraine sequences has the capacity to disrupt this interpretation and allow release and reworking of sediments for many decades, if not centuries following deglaciation (Ballantyne, 2002b; Curry *et al*., 2009) with enhanced availability of sediments associated with deglaciation not always resulting in a consistent increase in sediment release and reworking (e.g. Cossart, 2008). This 'interrupted sediment cascade' (Curry *et al*., 2005, Figure 2) continues in an episodic manner, such that paraglacial slope adjustment following retreat and wasting since the Last Glacial Maximum may still impact upon erosional and mass movement processes operating today (e.g. Kellerer-Pirklbauer *et al*., 2010; Vehling *et al*., 2016).

The geotechnical properties of lateral moraine sediments offer one avenue of investigation towards a fuller understanding of lateral moraine stability. Whalley (1975) was able to characterise various mechanical aspects of lateral moraines at the Feegletscher, Switzerland and calculated a friction angle of 45°, while suggesting that soil suction may have a role to play in enhancing slope strength and therefore stability. Distally dipping fabric, evident with clastic material > 0.5m long, results in imbrication of the Feegletscher moraines and might be expected to enhance stability as a result. However, the presence of steep, stable moraines with proximally dipping fabric observed elsewhere suggests that a distal dipping fabric is not a requirement for stability and extreme slope angles (Whalley, 1975). *In situ* studies carried out at the same location, combined with geotechnical laboratory tests of extracted samples from upper high-angle (< 80°) slope units, indicate that imbricated and proximally dipping mica-schist clasts inhibit shallow translational shear on the proximal slopes, which may assist in the retention of stable form at this site (Curry *et al*., 2009, Figure 1C). A 'buttressing' effect provided by the inter-gulley slopes is also speculated to assist in slope stabilisation, with suction effects potentially enhancing surface crust formation, but with limited impact on long-term stability (Curry *et al*., 2009).

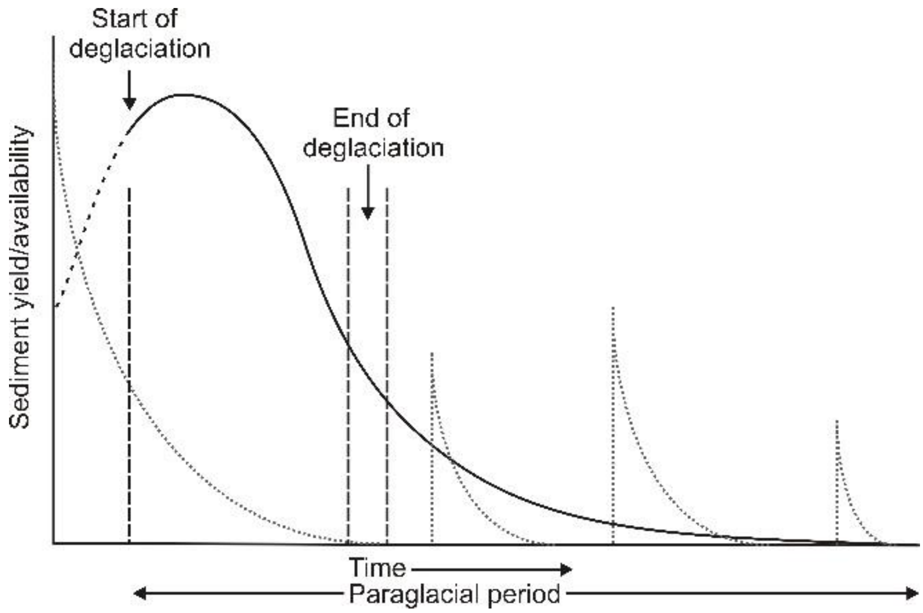


Figure 2. *Paraglacial models illustrating catchment sediment responses to deglaciation. The solid black curve illustrates the classic model proposed by Church and Ryder (1972), whereby basin sediment yields progressively decline with time since deglaciation. The dashed grey curves illustrate responses to deglaciation conditioned by sediment availability/exhaustion as proposed by Ballantyne (2002b), with episodic events taking place during and after deglaciation conditioned by, for example, extreme rainfall events (adapted from Ballantyne, 2002a).*

A comprehensive sedimentological study of lateral moraine morphology and properties carried out at Findelengletscher, Switzerland (Lukas *et al*., 2012) provides further information on lateral moraine genesis and resultant factors that may influence slope stability and resultant potential for sediment release and reworking. Rather than a dominant supraglacial source for lateral moraine sediments, subglacial and glaciofluvial sediments dominate, deposited by debris flows once material has been transferred from the bed to the ice surface via englacial pathways. Key however to proximal slope stability is the process of overconsolidation. Lukas *et al*. argue that this overconsolidation arises through a combination of glaciotectonisation of pre-existing sediments and incremental 'plastering' of till onto the proximal slopes of lateral moraines by moving ice. The resulting overconsolidation is suggested to be an important factor in enhancing slope stability, retarding paraglacial slope modification and consequently enhancing preservation potential and is regarded as a potentially widespread process that may offer an explanation for slope stability and the extreme slope angles often in excess of 80° as observed at Findelengletscher, without having to invoke the presence of a distally dipping fabric, a feature not ubiquitous to all lateral moraines (Curry *et al*., 2009; Lukas *et al*., 2012).

The stability and steepness of proximal lateral moraine slopes often gives rise to cross-sectional asymmetry, with distal slopes exhibiting lower slope angles, although it should be noted that cross-sectional asymmetry is not a ubiquitous observation (Lukas and Sass, 2011). In contrast to steep proximal slopes, lower-angled distal slopes, that usually represent depositional fan surfaces resting at the angle of repose, are generally less prone to intense paraglacial modification and the formation of gullies and, as such, tend to become more readily stabilised by vegetation cover (Figure 3). During deglaciation therefore, paraglacial modification of slope form may act to release sediments for reworking, while vegetation colonisation acts to decrease geomorphological activity and stabilise slope form where conditions are conducive to that colonisation (Matthews, 1992; Ballantyne, 2002a; Eichel *et al*., 2015). Conversely, at sites in the Norway and the central Swiss Alps, Curry (1999) and Curry *et al*. (2005) suggest that progressive vegetation colonisation on geomorphologically-active proximal moraine slopes is thought to be a response to slope stabilisation, rather than a causal factor. The role of vegetation acting to stabilise, or arising as a result of stabilisation and enhancing longer-term stability, therefore adds further complexity to the functioning of lateral moraines as both stores and sources of sediment. Feedback between vegetation and geomorphic process is likely to strongly condition slope form, but the details of this feedback are incompletely understood (Eichel *et al*., 2015; chapter 7.2) and represent an important area for further research, as deglaciation and vegetation colonisation gather pace in many locations.

Reworking of lateral slopes

Where paraglacial reworking does take place on lateral moraines, it frequently gives rise to dissection of moraine slopes, formation of gullies and redistribution of sedimentary materials, with associated colluvial debris cones and fans accumulating at the slope foot (e.g. Curry and Ballantyne, 1999; Curry *et al*., 2005; Curry *et al*; 2009; Lukas *et al*., 2012, Figure 1B and 1C). Clearly this dissection of moraines provides evidence of mass movement and resultant redistribution and transfer of sediment to the glacier surface or, where glacier retreat has left the moraine unit wholly exposed, the proglacial zone. Despite their apparent large-scale overall stability, steep lateral moraines are therefore potentially important conditioning factors for paraglacial slope modification (Curry *et al*., 2009) and represent a dynamic environment that may provide an efficient transport link between hillslopes and other geomorphic systems such as channelised flow in forefield areas (Cavalli *et al*., 2013; Eichel *et al*., 2015). However, in common with studies of lateral moraine formation and internal structure, paraglacial modification of slope form generally (Curry, 1999; Curry, 2000) and lateral moraine form in particular (Lukas *et al*., 2012) has received relatively scant research attention to date.

Paraglacial modification of lateral moraine slope form can take place through a variety of processes, including debris flowage, debris slides, stream action, solifluction, snow avalanching and stream action (Ballantyne, 2002a; Curry *et al*., 2006; chapter 4.4). Such processes are largely responsible for the characteristic paraglacial landscapes of gullied lateral moraines and valley sides, slope foot debris cones, fans and valley-floor deposits (Ballantyne and Benn, 1994; Ballantyne, 1995, Curry, 1999; Curry *et al*., 2006, Figure 1A). It is clear that extensive paraglacial modification of slope form through, for example, gullying, can take place within short timescales of the order of a few decades (e.g. Ballantyne and Benn, 1994) and that debris flow activity is one of the prime agents responsible for the redistribution of glacial sediments contained within hillslopes or moraines. Obvious flow tracks, levées and debris cones are often visible (e.g. Eyles and Kocsis, 1988; Owen, 1991; Ballantyne and Benn, 1994, Curry 2000), and rainfall (e.g. Chiarle *et al*., 2007) and rapid snowmelt and resultant liquefaction (e.g. Ballantyane and Benn, 1994; Palacios *et al*., 1999; Curry, 2000) are key triggers in many debris flow events. However, the precise controls on the extent and efficacy of debris flowage and other paraglacial hillslope activity represent a relatively under-studied aspect of deglaciation terrain relaxation (Curry, 2000). Studying paraglacial modification of glaciogenic slope sediments in western Norway, Curry (2000) utilises gully density as a surrogate indicator of paraglacial modification of sediments within lateral moraines. In common with other studies of paraglacial slope modification (e.g. Curry *et al*., 2005; Curry *et al*., 2009; Cavalli *et al*., 2013), debris flow activity emerges as a dominant mechanism, with snow avalanches representing a secondary paraglacial process. Of several intrinsic and extrinsic conditioning factors studied that may influence paraglacial debris flow activity, slope gradient, sediment availability and water supply emerge as important factors. However, a relative lack of paraglacial slope modification even in high relief areas demonstrates a clear need for a fuller understanding of the detailed constraints on paraglacial activity (Curry, 2000).

One obvious constraint is sediment supply and this aspect of paraglacial activity warrants a re-evaluation of the original Church and Ryder model that emphasises time as the key variable dictating paraglacial sediment supply, release and reworking, with maximum sediment supply occurring shortly after deglaciation and then steadily declining as glacier shrinkage continues (Church and Ryder, 1972). Ballantyne (2002b) therefore suggests that an exponentially-declining exhaustion model might be more appropriate, with sediment yield being dictated by sediment availability and perturbations in yield being dictated by factors such as changing base level or episodic sediment release from, for example, hillslopes during extreme rainfall events (Figure 2, Ballantyne, 2002b). This concept of sediment availability as a key controlling factor has significance when considering the role that hillslopes may play as stores and sources of sediment in a deglaciating landscape. Indeed, Curry (1999) suggests that upslope sediment availability is a likely control on slope stabilisation and to a certain extent, the delivery of sediments from ice-marginal hillslopes itself ensures a continuously diminishing supply of sediment and longer term stability, as debris flowage delivers material to the slope foot, progressively burying upper slope units, reducing slope gradient, reducing upslope sediment supply and potentially facilitating slope stability, with vegetation colonisation furthering stability (Figure 1B).

Considering lateral moraine materials further up-valley, the supraglacial accumulation of sediments sourced from adjacent hillslopes clearly represents an important input to lateral moraines. Although there is an extensive literature on debris-covered glaciers (see also section 3.3), the extent to which ice-marginal sediment delivery to a glacier surface may be regarded as strictly paraglacial in nature is open to question. Although we do not consider rockfall delivery in this section, it is thought that enhanced rockfall activity is a likely consequence of deglaciation (e.g. Fischer *et al*., 2006; Stoffel *et al*., 2014; chapters 4.1 and 4.2) and it seems not unreasonable to assume that ice-marginal sediment delivery to a glacier surface is also likely to increase as deglaciation continues, through processes of debuttressing (in instances where sedimentary slope units are being supported by the glacier), melt of permafrost that is acting to stabilise sedimentary units and through a general increase in water supply, associated with ice melt and shifting in the relative proportions of precipitation from snow to rainfall. Potential links between deglaciation and delivery of ice marginal sediments to the glacier surface have been demonstrated in Arctic settings (e.g. Porter *et al*., 2010) and there is a clear need for further research to assess the links between slope sedimentary systems and supraglacial systems in alpine settings, particularly considering the impact that surface debris cover can have on glacier melt, behaviour and ultimately moraine formation (e.g. Reznichenko *et al*., 2011). It is also becoming increasingly clear that a genetic origin for lateral moraines based wholly upon supraglacial accumulation of sediments derived from valley-side slopes may not appropriately explain formative mechanisms. The presence of sub- and en-glacial sediments and glaciofluvial deposits within lateral moraines highlights the potential importance of alternative mechanisms for supraglacial sediment accumulation and subsequent reworking through processes such as thermo-erosion and debris flow activity (e.g. Etzelmüller, 2000; Irvine-Fynn *et al*., 2011; Lukas *et al*., 2012; Porter *et al*., 2010; Tonkin *et al*., 2017).

FOREFIELD SLOPES

Formation and fluxes

Although often less visually obvious than large lateral moraine and valley side glaciogenic sediment sequences, the often extensive suites of moraine landforms commonly observed in deglaciating forefields represent a dynamic source and store of glacial sediments and exhibit characteristics of primary and secondary paraglacial activity. Although forefield slope gradients are typically lower than those observed on lateral moraine slopes, the presence of often spatially extensive and high-energy fluvial activity in the proglacial area (chapters 5.1 and 5.2) offers an important means of sediment transport and re-distribution, making the forefield area the most dynamic part of the alpine sediment flux system (Fenn and Gurnell, 1987; Warburton, 1990; Maizels, 1993; Marren, 2005; Otto *et al*., 2009). The presence of ice cores within proglacial moraine structures adds additional interest, as not only do ice cores potentially influence sub-surface drainage pathways with potential slope stability implications (e.g. Langston *et al*., 2011; Muir *et al*., 2011), but thermo-erosion offers an additional mechanism of sediment release from moraine slope units, aided by associated meltwater supply. There is extensive existing literature detailing mechanisms and processes of glaciofluvial entrainment, transport and deposition within proglacial environments and useful overviews can be found in Gurnell and Clarke (1987), Warburton (1990), Marren (2005) and Lane *et al*., (2017). Likewise, the genesis, morphology and structure of ice-marginal moraines is an area that has received much research attention and we would direct readers to Bennett (2001) and Barr and Lovell (2014) as useful starting points for discussion of these aspects of glacial geomorphology. As with the previous section concerning lateral slope forms and processes, in this section we confine our consideration to discussion of the role of moraine proglacial landforms as potential stores or sources of sediment and consider the mechanisms and extent of paraglacial activity operating on moraine slope units to further the redistribution of glaciogenic sediments in deglaciating environments.

Glacier forefields are necessarily comprised of deposits that reflect multiple episodes of erosion, transport and deposition, having inevitably been subject to the operation of multiple geomorphological processes and can be viewed as transitioning from glacial to non-glacial conditions (Heckmann *et al*., 2013). The diversity and morphological characteristics of forefield deposits will broadly reflect processes of sediment production and modification beneath the glacier, forefield geomorphological activity and glacier dynamics and in particular, the glacial response to deglaciation and the extent of any reworking and redistribution by meltwater (Orwin & Smart, 2004a). Exposure through glacier retreat and thinning makes deposits potentially available for re-mobilisation, transport and deposition by non-glacial processes, the presence of flowing water in the form of proglacial meltwaters being a particularly effective agent of erosion in a geomorphological context of abundant sediment supply, with observations indicating that up to 80% of total suspended sedment yield in proglacial rivers may be sourced from the forefield area (Orwin and Smart, 2004b). However, given the likely complexity of the genetic history of forefield sediments, they will comprise a wide range of deposits of varying ages and therefore varying stability and vulnerability to reworking (Orwin & Smart, 2004a). For example, negative feedback in some areas of deglaciating basins (e.g. transient storage of sediment in slope-foot debris cones) can act to reduce, rather than increase, basin sediment yields, through a decline in sediment system connectivity, despite increases in that connectivity elsewhere in the basin in response to deglaciation (e.g. Lane *et al*., 2017). Indeed, the extent to which the recently deglaciated forefield might represent a source or a sink for sediments is open to conjecture. Observed in an Arctic setting, Hodgkins *et al*. (2013) found that the extent to which the forefield zone may act as a net sink or a source of sediments may depend upon factors such as the nature of the temporally variant runoff regime, while age since exposure also likely represents an important factor in dictating vulnerability to reworking (e.g. Orwin and Smart 2004a), reflecting the generalised form of the paraglacial model of declining sediment yield as time since deglaciation advances (e.g. Church and Ryder, 1972, Figure 2).

At the basin scale, it is common for the forefield to be dominated by a relatively flat glacio-fluvial plain that extends from the glacier margin (Marren, 2005). In alpine environments, the forefield environment is typically delineated laterally by steep valley-side slopes and potentially high and steep lateral moraines, while the frontal margin is often marked by a prominent moraine (e.g. Figure 3), invariably breached by flowing meltwaters. This frontal moraine is often the most morphologically distinctive forefield moraine form (Benediktsson *et al*., 2009) and in alpine environments terminal or end moraines are usually associated with maximum recent glacier advance during the Little Ice Age (Figure 3A). Dependent on age, spatial extent and intensity of geomorphological activity, end moraines may support vegetation cover, particularly on distal slopes (Figure 3A), but equally, exposed sediments will be vulnerable to processes of reworking and redistribution. The stability of these moraines is a topic that has attracted much recent interest in the light of deglaciation and resultant formation of proglacial water bodies dammed behind terminal or end moraines with consequent risk of glacier lake outburst floods (GLOFs) should the moraine dam be breached (e.g. Stoffel and Huggel, 2012; Westoby *et al*., 2014; Ashraf *et al*., 2015. See also section 5.3).

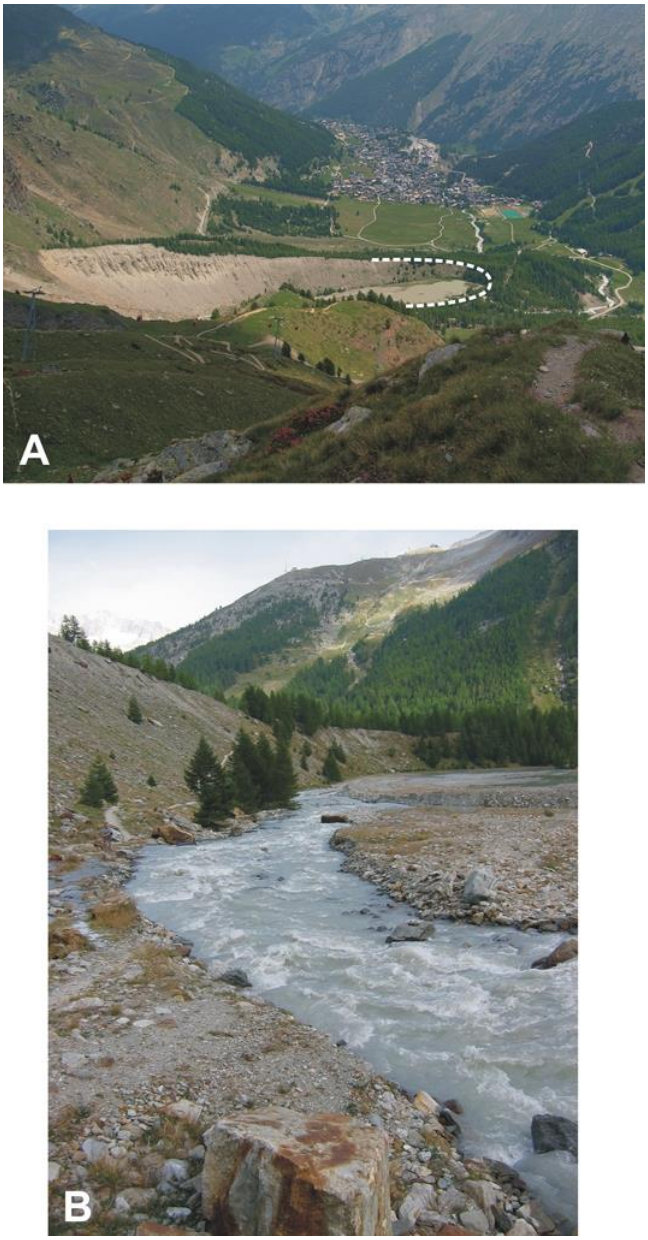


Figure 3. *A. Terminal moraine of the Feegletscher Nord, Valais, Switzerland. A. Dashed line indicates approximate location of the glacier front during the Little Ice Age maximum. Note the heavily vegetated distal slopes of the*

terminal moraine. B. View towards the terminal moraine from the promixal side. Note the mature vegetation on the stable proximal slopes of the terminal moraine to the far left of the image and the potential for slope foot fluvial transport where the proglacial meltwater stream impinges on the moraine in the middle distance.

The sediments stored within the forefield area are typically characterised by substantial volumes of the products of glacier erosion, and are usually dissected by meltwater streams with resultant capacity for extensive glacio-fluvial reworking and redistribution (e.g. Warburton, 1990; Hodgkins *et al*., 2003; Orwin & Smart, 2004a; Leggat *et al*., 2015). It is not uncommon for deglaciating forefields to be further characterised by a diverse range of glacial, fluvial and non-glacial landforms, features and deposits. Setting aside the glacio-fluvial landforms, stores and processes that are considered elsewhere in this volume (chapter 5.1), it is the diverse groups of moraines that are particularly important when considering paraglacial activity operating within the forefield area, although clearly relief and slope angles are both likely to be lower on average than that observed in recently deglaciated lateral locations.

Forefield moraines are an important source of information about the extent and dynamics of glaciers and ice masses. Consequently, they have been extensively studied and, despite the fact that mechanisms of formation remain manifold (Hiemstra *et al*., 2015), they have been widely used as an indirect proxy for climatic variation and past glacier dynamics and extents (e.g. Benn & Ballantyne 2005; Beedle *et al*., 2009; Evans *et al*., 1999). Numerous moraine types and classifications exist, leading to a complex picture in part due to 'inconsistent terminology' (Winkler and Matthews, 2010, p87) with sometimes 'incompatible' interpretations of the same landform being made (Evans *et al*., 1999, p673) and confusion being heightened by restricting moraine analysis to geomorphology alone, without a detailed consideration of the detailed sedimentology of moraines that is evident in more recent work (e.g. Lukas *et al*., 2012, Reinardy *et al*., 2013; Chandler *et al*., 2016). Given the dynamic nature of proglacial environments and associated potential for moraine modification and even potential eradication by a range of post-depositional processes (Kirkbride & Brazier, 1998; Kirkbride & Winkler, 2012), preservation potential is variable, as will be the role that moraines play in the storage and supply of sediment. The extent to which moraines may provide an accessible source of sediment for reworking and redistribution will depend upon myriad factors including, but not limited to: time since exposure, slope angle, degree of glaciotectonisation and compaction, the presence of an ice core and associated de-icing and thermo-erosion, the nature and extent of vegetation colonisation and the degree of transport and supply/weathering limitations.

REWORKING OF FOREFIELD SLOPES

Buried ice

The presence and subsequent prolonged degradation of buried remnant glacier ice within moraine landforms may influence moraine formation, morphology, slope activity and flow of meltwaters and groundwater in the forefield area (e.g. Kjær and Krüger, 2001; Langston *et al*., 2011; chapter 3.6). Retreating debris-covered glaciers can leave forefields of ice-cored forms and ice-rich debris (e.g. Bosson *et al.*, 2015) and this is particularly true close to the ice-margins, where dead ice can be incorporated during the process of moraine formation (Lukas *et al*., 2012). Ice-cores may survive decades to millennia and at considerable distances from the active ice margins (Barr & Lovell, 2014) and their degradation is typically evident as backwasting (i.e. lateral retreat) and downwasting (i.e. thinning, Krüger & Kjær, 2000), commonly giving rise to inverted topography and the reworking of sediments due to slumping, fall-sorting and the formation of features such as sinkholes, extension fractures, kettles, cracks, slips and mud/debris flows (Johnson, 1971; Kjær and Krüger, 2001). The redistribution and remobilisation of sediments can also be facilitated further by ice core melt and consequent sediment mobilisation, where removal of slope sediments through, for example, slumping or other slope mass movement exposes ice which is then vulnerable to thermo-erosion and backwasting (e.g. Kjær and Krüger, 2001; Schomacker & Kjaer 2007). Similarly, slow melt of buried ice can initiate sinkhole formation and associated collapse of slope units through undermining, and over-steepening of adjacent slopes that may initiate processes such as sliding and backslumping (Kjær and Krüger, 2001).

These processes of slope readjustment in response to a melting ice core and consequent sediment redistribution, may be enhanced through fluvial induced thermo-erosion where meltwaters are present. It is well established that fluvial activity plays an important role in shaping the detailed morphology of forefield landscapes (e.g. Carrivick *et al*., 2013), primarily through the mechanical processes of entrainment, transport and deposition and where flowing water is able to remove surficial deposits and expose buried ice, melt will progress rapidly. However, the presence of buried ice may also modify and partially dictate the location and efficacy of sub-surface water flow paths and it has been established that moraines can contain complex subsurface hydrological systems associated with the presence and interaction of sediments, buried and ground ice and bedrock (Langston *et al*., 2011).

Buried ice can act in two key ways to modify sub-surface drainage. Firstly, ice can act as an aquiclude, presenting a relatively impermeable barrier to sub-surface waters, controlling the routing of water. Secondly, buried ice may act as a source of water through the ongoing process of slow, sub-surface melting, or through rapid melting where ice becomes exposed at the surface. The accumulation of water in response to any sub-surface ice melt also offers the potential for saturation of sediments, with resultant implications for slope stability should that saturation destabilise slope units or indeed penetrate to surface sediment horizons. In Arctic settings, collapse of moraine sediments through melt of buried ice provides a potentially important component of the sediment cascade as a means of releasing sediments for redistribution, with resultant impact on moraine slope form and basin sediment yield (e.g. Etzelmüller, 2000; Etzelmüller et al., 2000; Lyså, and Lønne, 2001; Lukas *et al*., 2005; Porter *et al*., 2010; Irvine-Fynn *et al*., 2011). Where subsurface ice and water are in contact there is also the potential for effective thermo-erosion. However, largely due to a paucity of field observations and the practical difficulties of assessing both sub-surface water flow and ice presence and characteristics, the detailed role of forefield moraine landforms in controlling subsurface water storage and flow remains poorly constrained (Langston *et al*., 2011) and by implication, so do the resultant influences upon surface slope processes and stability.

Hydrological interactions

It is well established that sediment transfer within, and from, deglaciated forefields reflect the competing controls of sediment supply and the efficacy of transport processes (e.g. Warburton, 1990; Hodgkins *et al*., 2003). Networks of high-energy streams and rivers typically dominate the downstream transfer of glacigenic sediments from forefield environments and fluvial processes are one of the primary agents of within-catchment landscape change due to their pivotal role in forefield sediment reworking and redistribution (Warburton, 1990; Marren, 2005; Carrivick *et al*., 2013; Lane *et al*., 2017).

The impact of fluvial-slope interactions has its most obvious morphological expression where forefield moraines have been dissected by meltwater channels. Such dissection will arise through ‘normal’ processes of glaciofluvial erosion, but more extreme examples of dissection and associated slope modification have been associated with outburst floods (e.g. Staines *et al*., 2014) or the failure of moraine dams in mountain environments (e.g. Korup & Tweed, 2007). However, there are limited quantitative data available to establish the overall importance of such large-scale sediment redistribution events in re-mobilising and redistributing sediments as deglaciation terrain relaxation takes place, nor to establish the likely recurrence of such events (Ballantyne, 2002a; Beylich & Warburton, 2007). More commonly, there will be ‘normal’ or ‘continuous’ post-depositional modification of forefield landforms through the action of flowing meltwater, interspersed with discrete, extreme events (e.g. Cossart, *et al*., 2008; Carrivick *et al.,* 2013).

The impact of connections between slope and glaciofluvial sedimentary systems and resultant landform modification are most evident at the margins of proglacial streams, where fluvial processes may directly interact with hillslope units, presenting the most obvious sign that sediment is being delivered from the slopes to the valley floor (Beylich & Warburton, 2007; Cavalli *et al*., 2013, Figure 3B). Any resulting erosion not only modifies slope form, but may potentially generate slope instability through processes of undercutting and resultant collapse (Iturrizaga, 2008; Winkler & Matthews 2010). Direct proglacial channel margin erosion will be limited to the valley floor, however, upslope instability may be induced and only become apparent when slopes are destabilised and mass movements occur (Orwin & Smart, 2004; Schrott *et al*., 2006).

It is clear that fluvial activity plays an important role in moraine morphological modification and associated release of sediments and that forefield sediments generally can contribute significantly to total basin sediment yield (e.g. Warburton, 1990; Orwin & Smart, 2004a; Leggat *et al*., 2015) and in an episodic fashion in the case of mass movements (Schrott *et al*., 2006; Carrivick *et al*., 2013). However, over time the hydrological efficacy of flowing water in mobilising forefield sediments is likely to decline. This arises from the eventual decline of the 'deglaciation dividend' (Kaser *et al*., 2010), whereby the initial enhanced melt, or dividend, associated with deglaciation reduces. Aside from this dwindling supply of meltwaters in the latter stages of deglaciation, surface sediments and slopes are likely to stabilise because of eluviation of fines and progressive armouring of surface layers caused by processes such as overland flow and rainsplash. This process can take place rapidly and forefield surfaces may cease to function as significant sources of sediment within decades of deglaciation and exhibit stability to all but extreme events (Orwin and Smart 2004a).

The reworking and redistribution by meltwater of sediments within moraines may eventually lead to a situation where much of the forefield will comprise reworked glaciogenic material (Carrivick *et al.*, 2013) such that relief becomes subdued and the area of meltwater river channels increases (Staines *et al.*, 2014). Forefield slope stability will likely be restricted to areas unaffected by fluvial activity or ice-core degradation (Ewertowski *et al.*, 2010). This increase in slope stability and consequent decrease in sediment availability and mobilisation with time has been evident from studies of the patterns of aggradation and degradation in glacier forefields, where geomorphological activity decreases in both spatial extent and in intensity with distance from the glacier and by implication, time since deglaciation (e.g. Orwin and Smart, 2004a). Hillslope activity will then likely become restricted to inherently unstable slopes, or those unaffected by or resistant to fluvial activity. As deglaciation continues, fluvial activity in general will progressively become more important. However, the apparent stability and persistence of moraine landforms and sediments observed in contemporary forefield areas suggests that the reworking and redistribution of deposits by fluvial activity may not be spatially extensive and that geomorphological activity is increasingly dominated by the interactions with specific processes (e.g. fluvial) over relatively small areas of catchments (Carrivick *et al.*, 2013) or by the occurrence of extreme high-magnitude, episodic, low-frequency events such as those induced by changes in temperature or precipitation (Stoffel and Huggel, 2012; Blair, 1994).

The importance of episodic rainfall events in mobilising sediments from forefield slopes has been noted in a number of studies (e.g. Richards, 1984; Kellerer-Pirkbauer *et al*., 2010; Cavalli *et al*., 2013; Leggat *et al*., 2015; chapter 4.4) and can be responsible for both destabilising slopes (Blair, 1994; Deline *et al*., 2015) and contributing to the exhaustion of supplies of fine sediments, with resultant reduction in overall sediment mobilization (Orwin & Smart, 2004b). The role of precipitation as a sediment transfer mechanism may become increasingly important during deglaciation due to the increasing proportion of total runoff comprising liquid precipitation as stores of snow and ice deplete (Collins, 2008), while rainfall-induced extreme discharge events clearly have the capacity to mobilise even well-armoured and stabilised forefield sediments (e.g. Luckmann, 1981), interrupting the theoretical uni-directional decline in basin sediment yield as deglaciation progresses. Given forecast changes in precipitation frequency and intensity associated with climate change (Stoffel and Huggel, 2012), the potential for precipitation events to further affect basin sediment yields is only likely to increase.

ENVIRONMENTAL CHANGE AND ALPINE PARAGLACIAL ACTIVITY

As the impacts of climate change are becoming more obvious in alpine regions, an increased interest in interactions and feedbacks between paraglacial activity and associated biogeographical and hydrological processes has developed. In the European Alps for example, larger magnitude debris flow events may become increasingly common due to predicted increases in autumn and spring rainfall, permafrost melt and enhanced sediment delivery (Stoffel *et al*., 2014). It is also hypothesised that, given the combination of enhanced sediment availability, permafrost degradation and changes in rainfall, debris flow events with ‘little or no historical precedent’ could be facilitated (Stoffel and Huggel, 2012, p430).

To date, catchment-scale studies of paraglacial activity have largely focussed upon the storage, release and reworking of sediments. However, as climate warms, there is also a need to consider the related issues of enhanced biological and hydrological activity that develop in tandem with enhanced storage and transfer of sedimentary materials. It is becoming increasingly clear that any consideration of the landscape response to deglaciation cannot be considered in isolation from the closely-associated hydrological and biological responses. In addition to enhancing the vulnerability of sediments to processes of reworking and redistribution, glacier retreat and down-wasting makes those same sediments available for microbial colonisation, with resultant build of up nutrient pools that encourage pedogenesis and increased organic matter development (e.g. Bernasconi *et al*., 2008; Schurig *et al*., 2013). In response to increased soil, organic matter and nutrient availability, vegetation succession is initialised, leading ultimately to the growth of higher order plants that may play an important role in conditioning slope stability (Bradley *et al*., 2014; Eichel *et al*., 2015; chapter 7.2). Indeed, vegetation-landform interactions are becoming increasingly recognised as an important, albeit under-studied, aspect of the landscape response to deglaciation, with the result that the discipline of ‘biogeomorphology’ is currently seen to be an actively developing and useful means of enhancing understanding of forefield dynamics

(Eichel *et al*., 2013; Eichel *et al*., 2015). Rapid deglaciation and revelation of ice-marginal and forefield sediments also offers opportunities to study in detail the mechanisms of and factors determining the efficacy of vegetation colonisation and succession (e.g. Jumpponen *et al*., 1999).

It has been established that the extent and stage of vegetation colonisation is a likely strong determinant of sediment availability and catchment sediment yield (Ballantyne, 2002a; Klaar *et al*., 2015) and, in general terms, vegetation succession and associated ecosystem complexity will develop on a similar timescale to the progressively declining sediment yield assumed in many paraglacial models (Ballantyne, 2002a; Klær *et al*., 2015, Figure 2). For slope units that are not subject to regular disturbance from geomorphological activity, vegetation colonisation impacts paraglacial adjustment through the stabilisation of landforms and a resultant decline in sediment availability as the paraglacial ‘period’ progresses (Ballantyne, 2002a; Orwin and Smart, 2004b; Marston, 2010; Klaar *et al*., 2015;). As vegetation colonisation progresses, sediment cohesion and shear strength increase and rainfall interception and infiltration become enhanced, thereby reducing surface runoff and likelihood of surface sediment mobilisation (Klær *et al*., 2015).

However, in much the same way that a simple uni-directional decline in sediment yield may not adequately describe the reality of the landscape response to deglaciation (e.g. Ballantyne 2002b, Figure 2), vegetation succession may also be interrupted by geomorphic processes (Matthews, 1992) dependent on magnitude and frequency (Eichel *et al*., 2013), resulting in the persistence of younger successional stages of vegetation colonisation (e.g. Eichel *et al*., 2013) with resultant impacts on sediment availability. Feedbacks and relationships between geomorphic systems and vegetation ecosystems are therefore potentially complex and the details of microbial and subsequent vegetation colonisation and consequent impacts on slope stability and sediment redistribution (or stability-induced lack thereof) are presently obscure (Klaar *et al*., 2015) and represent a current research priority.

In terms of hydrological impacts, glacial and associated sediments and moraines play an important role in controlling the timing and quantity of water release from glaciated catchments (e.g. Langston *et al*., 2011; Cook *et al*., 2013), with any paraglacial modification potentially altering the nature and functioning of water flow paths, with resultant impacts on the quantity and timing of basin water yields and the ecology of meltwater-fed ecosystems (e.g. Brown *et al*., 2006; Milner *et al*., 2009). Forefield surface glacial sediments, such as those contained within moraines, can play an important role in temporarily storing and thereby buffering basin meltwater discharge and sustaining baseflow, but the processes of water storage and transfer through moraines and other depositional glacial landforms remain obscure (Langston *et al*., 2011). Given the likely increasing intensity of sediment redistribution associated with deglaciation, understanding the associated impacts on meltwater flow specifically and basin hydrology generally represents an important area for further research, especially considering the significant reliance on meltwater as a resource in many alpine regions.

CONCLUSION

As deglaciation in alpine regions continues, research interest in the resultant impacts on sediment storage, release and reworking is likely to become further enhanced, adding to the growth of interest in paraglacial geomorphology identified by Ballantyne (2002a). Great uncertainty still exists, however, concerning the timescales over which the geomorphological response to deglaciation persists (Dadson and Church, 2005) and the subsequent patterns of sediment release from basins during deglaciation. The basic notion of maximal sediment delivery immediately following deglaciation, followed by a slow, uni-directional decline as slope units and other terrain surfaces stabilise, may be broadly appropriate over large timescales. However, over shorter timescales, it is clear that enhanced delivery of sediments from slope units is not an inevitable or immediate consequence of deglaciation and that a variety of geological, geomorphological, hydrological and biogemorphological factors will inevitably add a somewhat stochastic element to patterns of sediment release. Understanding these patterns of sediment release and indeed spatial and temporal variations in sediment storage, represents an important area of current glaciological research, as contemporary deglaciation offers an unparalleled, albeit ultimately time-limited, opportunity to directly observe the genesis of deglaciation-landforms, their modification and associated sediment fluxes and fluctuations in basin-scale sediment storage. This not only permits a fuller understanding of the complexities of the geomorphological processes during deglaciation, but contributes to enhanced understanding of glacial depositional landform genesis. Furthermore, with rapid warming evident in alpine regions, melt of permafrost and a predicted greater frequency of extreme precipitation events have the potential to remobilise the substantial glaciogenic sediment stores that are present in many alpine regions. It is therefore critical, both from a geomorphological and human impact point of view, that a fuller and detailed understanding of the processes that drive that remobilisation is gained, such that greater accuracy can be afforded to predictions of landscape development and associated potential impacts on human activity.

REFERENCES

Ashraf, A., Naz, R., and Iqbal, M.B., 2015. Heterogeneous expansion of end-moraine dammed lakes in the Hindukush-Karakoram-Himalaya ranges of Pakistan during 2001–2013. *Journal of Mountain Science*, 12 (5), 1113-1124.

Ballantyne, C. K., 1995. Paraglacial debris-cone formation on recently deglaciated terrain. western Norway. *The Holocene*, 5(1), 25-33.

Ballantyne C.K**.,** 2002a**.** Paraglacial geomorphology. *Quaternary Science Reviews,* 21, 1935-2017.

Ballantyne C.K**.,** 2002b. A general model of paraglacial landscape response. *The Holocene*, 12(3), 371-376.

Ballantyne, C. K. and Benn, D. I., 1994. Paraglacial slope adjustment and resedimentation in response to recent glacier retreat, Fåbergstølsbreen, Norway. *Arctic and Alpine Research*, 26, 255-269.

Barr, I. D., and Lovell, H., 2014. A review of topographic controls on moraine distribution. *Geomorphology*, 226, 44-64.

Barry, R.G., 2006. The status of research on glaciers and global glacier recession: A review. *Progress in Physical Geography*, 30(3), 285-306.

Beedle, M. J., Menounos, B., Luckman, B. H., & Wheate, R., 2009. Annual push moraines as climate proxy. *Geophysical Research Letters*, 36(20).

Benn, D. I. & Ballantyne, C. K., 2005. Palaeoclimatic reconstruction from Loch Lomond Readvance glaciers in the West Drumochter Hills, Scotland. *Journal of Quaternary Science,* 20(6), 577-592.

Benediktsson, Í.Ö., Ingólfsson, Ó., Schomacker, A., Kjær, K.H., 2009. Formation of submarginal and proglacial end moraines: Implications of ice-flow mechanism during the 1963-64 surge of Brúarjökull, Iceland. *Boreas*, 38(3), 440-457.

Bennett, M.R., 2001. The morphology, structural evolution and significance of push moraines. *Earth-Science Reviews*, 53, 197-236.

Bernasconi, S.M., Christi, I., Hajdas, I., Abbaspour, K., 2008. Weathering, soil formation and initial ecosystem evolution on a glacier forefield: A case study from the Damma Glacier, Switzerland. *Mineralogical Magazine*, 72(1), 19-22.

Beylich, A. A., and Warburton, J., 2007. Analysis of source-to-sink-fluxes and sediment budgets in changing high-latitude and high-altitude cold environments. *Sediflux manual* (1st ed.), NGU Report.

Blair Jr, R.W., 1994. Moraine and valley wall collapse due to rapid deglaciation in Mount Cook National Park, New Zealand. *Mountain Research & Development*, 14(4), 347-358.

Bosson, J. B., Deline, P., Bodin, X., Schoeneich, P., Baron, L., Gardent, M., and Lambiel, C., 2015. The influence of ground ice distribution on geomorphic dynamics since the Little Ice Age in proglacial areas of two cirque glacier systems. *Earth Surface Processes and Landforms*, 40(5), 666-680.

Bradley, J.A., Singarayer, J.S. and Anesio, A.M., 2014. Microbial community dynamics in the forefield of glaciers. *Proceedings of the Royal Society B: Biological Sciences*, 281 (1795), 20140882.

Brown, L.E, Milner, A.M. and Hannah. D.M., 2006. Persistence and stability of alpine stream macroinvertebrate communities and the role of physicochemical habitat variables. *Hydrobiologia,* 540, 159-173.

Carrivick, J.L. and Heckmann, T., 2017. Short-term geomorphological evolution of proglacial systems. *Geomorphology*.

Carrivick J.L., Geilhausen, M., Warburton, J., Dickson, N.E., Carver, S.J., Evans, A.J. and Brown, L.E., 2013. Contemporary geomorphological activity throughout the proglacial area of an alpine catchment. *Geomorphology*, 188, 83-95.

Cavalli, M., Trevisani, S., Comiti, F., and Marchi, L., 2013. Geomorphometric assessment of spatial sediment connectivity in small Alpine catchments. *Geomorphology*, 188, 31-41.

Chandler, B.M.P., Evans, D.J.A., Roberts, D.H., 2016. Characteristics of recessional moraines at a temperate glacier in SE Iceland: Insights into patterns, rates and drivers of glacier retreat. *Quaternary Science Reviews*, 135, 171-205.

Chiarle, M., Iannotti, S., Mortara, G., Deline, P., 2007. Recent debris flow occurrences associated with glaciers in the Alps. *Global and Planetary Change*, 56, 123–136.

Church M., Ryder J.M., 1972. Paraglacial sedimentation: consideration of fluvial processes conditioned by glaciation. *Geological Society of America Bulletin*, 83, 3059-3072.

Collins, D. N., 2008. Climatic warming, glacier recession and runoff from Alpine basins after the Little Ice Age maximum. *Annals of Glaciology*, 48(1), 119-124.

Cook, S.J., and Porter, P.R., Bendell, C.A., 2013. Geomorphological consequences of glacier advance across a paraglacial rock avalanche deposit. *Geomorphology*, 189, 109-120.

Cossart, E., Braucher, R., Fort, M., Bourlès, D.L., Carcaillet, J., 2008. Slope instability in relation to glacial debuttressing in alpine areas (Upper Durance catchment, southeastern France): Evidence from field data and 10Be cosmic ray exposure ages. *Geomorphology*, 95(1-2), 3-26.

Curry, A.M., 1999. Paraglacial modification of slope form. *Earth Surface Processes and Landforms*, 24(13), 1213-1228.

Curry, A.M., 2000. Observations on the distribution of paraglacial reworking of glacigenic drift in western Norway. *Norsk Geografisk Tidsskrift*, 54(4), 139-147.

Curry, A.M., and Ballantyne, C.K., 1999. Paraglacial modification of glacigenic sediment. *Geografiska Annaler*, Series A: Physical Geography, 81(3), 409-419.

Curry, A.M., Cleasby, V. and Zukowskyj, P., 2005. Paraglacial response of steep, sediment-mantled slopes to post-'Little Ice Age' glacier recession in the central Swiss Alps. *Journal of Quaternary Science*, 21, 211-225.

Curry, A.M., Sands, T.B., and Porter, P.R. 2009. Geotechnical controls on a steep lateral moraine undergoing paraglacial slope adjustment. *Geological Society Special Publication*, 320, 181-197.

Curry, A.M., Porter, P.R., Irvine-Fynn, T.D.L., Rees, G., Sands, T.B., Puttick, J., 2009. Quantitative particle size, microtextural and outline shape analyses of glacigenic sediment reworked by paraglacial debris flows. *Earth Surface Processes and Landforms*, 34, 1, 48-62.

Dadson, S.J., Church, M., 2005. Postglacial topographic evolution of glaciated valleys: A stochastic landscape evolution model. Earth Surface Processes and Landforms, 30(11), 1387-1403.

Deline, P., Hewitt, K., Reznichenko, N., & Shugar, D., 2015. Rock avalanches onto glaciers. *Landslide Hazards, Risks and Disasters*. Elsevier, Amsterdam, 263.

Dunning, S.A., Rosser, N.J., McColl, S.T., Reznichenko, N.V., 2016. Rapid sequestration of rock avalanche deposits within glaciers. *Nature Communications*, 6,7964.

Eichel, J., Krautblatter, M., Schmidtlein, S. and Dikau, R., 2013. Biogeomorphic interactions in the Turtmann glacier forefield, Switzerland. *Geomorphology*, 201, 98–110.

Eichel, J., Corenblit, D. and Dikau, R., 2015. Conditions for feedbacks between geomorphic and vegetation dynamics on lateral moraine slopes: a biogeomorphic feedback window. *Earth Surface Processes and Landforms*, DOI: 10.1002/esp.3859.

Etzelmüller, B., 2000. Quantification of thermo-erosion in pro-glacial areas-examples from Svalbard. *Zeitschrift für Geomorphologie*, 343-361.

Etzelmüller, B., Ødegård, R.S., Vatne, G., Tonning, T., Sollid, J.L. 2000. Glacier characteristics and sediment transfer system of Longyearbreen and Larsbreen, western Spitsbergen. *Norsk Geografisk Tidsskrift*, 54(4), 157-168.

Evans, D.J.A., Lemmen, D.S. and Rea, B.R., 1999. Glacial landsystems of the southwest Laurentide Ice Sheet: modern Icelandic analogues. *Journal of Quaternary Science*, 14(7), 673-691.

Ewertowski, M., Kasprzak, L., Szuman, I., & Tomczyk, A., 2010. Depositional processes within the frontal ice-cored moraine system, Ragnar glacier, Svalbard. *Quaestiones Geographicae*, 29(1), 27-36.

Ewertowskia, M.W., Tomczyka, A.M., 2015. Quantification of the ice-cored moraines' short-term dynamics in the high-Arctic glaciers Ebbabreen and Ragnarbreen, Petuniabukta, Svalbard. *Geomorphology*, 234, 211–227.

Eyles, N., 1983. The glaciated valley landsystem. In: Eyles, N. (Ed.), *Glacial Geology*. Pergamon, Oxford, pp. 91-110.

Eyles, N. and Kocsis, S.P., 1988. Sedimentology and Clast Fabric of a Glacially-influenced Alluvial Fan: Fraser River, British Columbia. *Sedimentary Geology*, 59, 15-28.

Eyles, N., Rogerson, R.J., 1978. Sedimentology of medial moraines on Berendon Glacier, British Columbia, Canada: Implications for debris transport in a glacierized basin. *Bulletin of the Geological Society of America*, 89(11), 1688-1693.

Fischer, L., Kääb, A., Huggel, C., and Noetzli, J., 2006. Geology, glacier retreat and permafrost degradation as controlling factors of slope instabilities in a high-mountain rock wall: the Monte Rosa east face. *Natural Hazards and Earth System Science*, 6 (5), 761-772.

Gurnell, A.M and Michael J. Clark, M.J. (Eds.), 1987. *Glacio-Fluvial sediment transfer: An alpine perspective*. John Wiley and Sons, Chichester.

Heckmann, T., Schwanghart, W., 2013. Geomorphic coupling and sediment connectivity in an alpine catchment – Exploring sediment cascades using graph theory. *Geomorphology*, 182, 89-103.

Hiemstra, J.F., Matthews, J.A., Evans, D.J.A and Owen, G., 2015. Sediment fingerprinting and the mode of formation of singular and composite annual moraine ridges at two glacier margins, Jotunheim, southern Norway. *The Holocene*, 25(11), 1772-1785.

Hodgkins, R., Cooper, R., Wadham, J. and Tranter, M., 2003. Suspended sediment fluxes in a high-Arctic glacierised catchment: implications for fluvial sediment storage. *Sedimentary Geology*, 162 (1–2), 105–117.

Hugenholtz, C.H., Moorman, B.J., Barlow, J., Wainstein, P.A., 2008. Large-scale moraine deformation at the Athabasca Glacier, Jasper National Park, Alberta, Canada. *Landslides*, 5(3), 251-260.

Hürlimann, M., Abancó, C., Moya, J., 2012. Rockfalls detached from a lateral moraine during spring season. 2010 and 2011 events observed at the Rebaixader debris-flow monitoring site (Central Pyrenees, Spain). Landslides, 9(3), 385-393.

Irvine-Fynn, T.D.L., Moorman, B.J., Sjogren, D.B., Walter, F.S.A., Willis, I.C., Hodson, A.J., Williams, J.L.M., Mumford, P.N. 2005. Cryological processes implied in Arctic proglacial stream sediment dynamics using principal components analysis and regression. *Geological Society Special Publications*, 242(1), 83-98.

Irvine-Fynn, T. N.E. Barrand, P.R. Porter, A.J. Hodson, T. Murray, 2011. Recent High-Arctic glacial sediment redistribution: A process perspective using airborne lidar. *Geomorphology* 125 (1), 27-39.

Iturrizaga, L., 2008. Paraglacial landform assemblages in the Hindukush and Karakoram Mountains. *Geomorphology*, 95(1), 27-47.

Johnson, P. G., 1971. Ice cored moraine formation and degradation, Donjek glacier, Yukon territory, Canada. *Geografiska Annaler*, Series A. Physical Geography, 198-202.

Jumpponen, A., Väre, H., Mattson, K.G., Ohtonen, R. and Trappe, J.M., 1999. Characterization of 'safe sites' for pioneers in primary succession on recently deglaciated terrain. *Journal of Ecology* 87 (1), 98-105.

Kaser, G., Großhauser, M., Marzeion, B., 2010. Contribution potential of glaciers to water availability in different climate regimes. *Proceedings of the National Academy of Sciences of the United States of America*. 107 (47), 20223-20227.

Keller-Pirklbauer, A., Proske, H. and Strasser, V., 2010. Paraglacial slope adjustment since the end of the Last Glacial Maximum and its long-lasting effects on secondary mass wasting processes: Hauser Kaibling, Austria. *Geomorphology*, 120, 65-76.

Kirkbride, M. P., and Brazier, V. 1998. A critical evaluation of the use of glacier chronologies in climatic reconstruction, with reference to New Zealand. *Journal of Quaternary Science*, 13(6), 55-64.

Kirkbride, M. P., and Winkler, S. 2012. Correlation of Late Quaternary moraines: impact of climate variability, glacier response, and chronological resolution. *Quaternary Science Reviews*, 46, 1-29.

Kjær, K. H., & Krüger, J. 2001. The final phase of dead - ice moraine development: processes and sediment architecture, Kötlujökull, Iceland. *Sedimentology*, 48(5), 935-952.

Klaar, M. J., Kidd, C., Malone, E., Bartlett, R., Pinay, G., Chapin, F. S., & Milner, A., 2015. Vegetation succession in deglaciated landscapes: implications for sediment and landscape stability. *Earth surface processes and Landforms*, 40(8), 1088-1100.

Korup, O., & Tweed, F., 2007. Ice, moraine, and landslide dams in mountainous terrain. *Quaternary Science Reviews*, 26(25), 3406-3422.

Krüger, J. & kjær, K. H., 2000. De-icing progression of ice-cored moraines in a humid, sub-polar climate, Kotlujökull, Iceland. *The Holocene*, 48, 935–952.

Lane, S.N., Bakker, M., Gabbud, C., Micheletti, N., Saugy, J.-N., 2017. Sediment export, transient landscape response and catchment-scale connectivity following rapid climate warming and Alpine glacier recession. *Geomorphology*, 277, 210-227.

Langston, G., Bentley, L.R., Hayashi, M. and McClymont, A.F. 2011. Internal structure and hydrological functions of an alpine proglacial moraine. *Hydrological Processes*, 25, 2967-2982.

Lebourg, T., Riss, J., Pirard, E., 2004. Influence of morphological characteristics of heterogeneous moraine formations on their mechanical behaviour using image and statistical analysis. *Engineering Geology*, 73(1-2), 37-50.

Leggat, M. S., Owens, P. N., Stott, T. A., Forrester, B. J., Déry, S. J., & Menounos, B., 2015. Hydrometeorological drivers and sources of suspended sediment flux in the proglacial zone of the retreating Castle Creek Glacier, Cariboo Mountains, British Columbia, Canada. *Earth Surface Processes and Landforms*, 40(11), 1542-1559.

Luckman, B.H., 1981. The geomorphology of the Alberta Rocky Mountains: a review and commentary. *Zeitschrift für Geomorphologie*, Supplementband, 37, 91–119.

Lukas, S. and Sass, O., 2011. The formation of Alpine lateral moraines inferred from sedimentology and radar reflection patterns - a case study from Gornergletscher, Switzerland. *Geological Society of London Special Publications*, 354, 77–92.

Lukas, S., Graf, A., Coray, S. and Schlüchter, C., 2012. Genesis, stability and preservation potential of large lateral moraines of Alpine valley glaciers - towards a unifying theory based on Findelengletscher, Switzerland. *Quaternary Science Reviews*, 38, 27-48.

Lyså, A. and Lønne, I., 2001. Moraine development at a small High-Arctic valley glacier: Rieperbreen, Svalbard. Journal of Quaternary Science, 16(6), 519–529.

Maizels, J., 1993. Lithofacies variations within sandur deposits: the role of runoff regime, flow dynamics and sediment supply characteristics. *Sedimentary Geology*, 85(1-4), 299-325.

Marren, P.M., 2005. Magnitude and frequency in proglacial rivers: a geomorphological and sedimentological perspective. *Earth-Science Reviews*, 70, 203–251.

Marston, R. A., 2010. Geomorphology and vegetation on hillslopes: interactions, dependencies, and feedback loops. *Geomorphology*, 116(3), 206-217.

Matthews, J.A., 1992. *The Ecology of Recently-deglaciated Terrain: A Geoecological Approach to Glacier Forelands*. Cambridge University Press, Cambridge.

Midgley, N.G., Cook, S.J., Graham, D.J., Tonkin, T.N., 2013. Origin, evolution and dynamic context of a Neoglacial lateral-frontal moraine at Austre Lovénbreen, Svalbard. *Geomorphology*, 198, 96-106.

Milner, A.M., Brown, L.E. and Hannah, D.M., 2009. Hydroecological effects of shrinking glaciers. *Hydrological Processes*. 23, 62-7.

Moore, R.D., Fleming, S.W., Menounos, B., Wheate, R., Fountain, A., Stahl, K., Holm, K. and Jakob, M., 2009. Glacier change in western North America: influences on hydrology, geomorphic hazards and water quality. *Hydrological Processes*, 23, 42-61.

Muir, D.L., Hayashi, M., Mcclymont, A.F., 2001. Hydrological storage and transmission characteristics of an alpine talus. *Hydrological Processes*, 25(19):2954-2966.

Müller, J., Gärtner-Roer, I., Kenner, R., Thee, R. and Morche, D., 2014. Sediment storage and transfer on a periglacial mountain slope (Corvatsch, Switzerland). *Geomorphology*, 218, 35-44.

Orwin, J.F. and Smart, C.C., 2004a. The evidence for paraglacial sedimentation and its temporal scale in the deglacerizing basin of Small River Glacier, Canada. *Geomorphology*, 58, 175–202.

Orwin, J.F. and Smart, C.C., 2004b. Short--term spatial and temporal patterns of suspended sediment transfer in proglacial channels, Small River Glacier, Canada. *Hydrologic Processes*, 18, 1521–1542.

Orwin, J., Lamoureux, S.F., Warburton, J. and Beylich, A., 2010: A framework for characterizing fluvial sediment fluxes from source to sink in cold environments. *Geogr. Ann*. 92 A (2): 155–176.

Otto, J., Schrott, L., Jaboyeoff, M. and Dikau, R., 2009. Quantifying sediment storage in a high alpine valley (Turtmanntal, Switzerland). *Earth Surface Processes and Landforms*, 34, 1726-1742.

Owen, L.A., 1991. Mass movement deposits in the Karakoram Mountains: their sedimentary characteristics, recognition and role in Karakoram landform evolution. *Zeitschrift für Geomorphologie*, 35(4), 401-424.

Palacios, D., Parrilla, G., Zamorano, J.J., 1999. Paraglacial and postglacial debris flows on a Little Ice Age terminal moraine: Jamapa Glacier, Pico de Orizaba (Mexico). *Geomorphology*, 28(1-2), 95-118.

Porter, P.R., Vatne, G., Ng, F., Irvine-Fynn, T.D. 2010. Ice-marginal sediment delivery to the surface of a High-Arctic glacier: Austre Brøggerbreen, Svalbard. *Geografiska Annaler*: Series A, Physical Geography 92 (4), 437-449.

Radić V., and Hock, R., 2011. Regionally differentiated contribution of mountain glaciers and ice caps to future sea-level rise. *Nature Geoscience*, 4, 91–94.

Reinardy, B.T.I., Leighton, I., Marx, P.J., 2013. Glacier thermal regime linked to processes of annual moraine formation at Midtdalsbreen, southern Norway. *Boreas*, 42(4), 896-911.

Reznichenko, N., Davies, T.R.H. and Alexander, D.J., 2011. Effects of rock avalanches on glacier behaviour and moraine formation. Geomorphology 132, 327-338.

Richards, K., 1984. Some observations on suspended sediment dynamics in Storbregrova, Jotunheimen. *Earth Surface Processes and Landforms*, 9(2), 101-112.

Röthlisberger, F. and Schneebeli, W., 1979. Genesis of lateral moraine complexes, demonstrated by fossil soils and tree trunks; indicators of postglacial climatic fluctuations. In Schlüchter, Ch. (ed.), *Moraines and Varves*, Balkema, Rotterdam, 387-419.

Schomacker, A., and Kjær, K. H., 2008. Quantification of dead-ice melting in ice-cored moraines at the high-Arctic glacier Holmströmbreen, Svalbard. *Boreas*, 37(2), 211-225.

Schulmeister, J., Davies, T.R., Evans, D.J.A., Hyatt, O.M. and Tovar, D.S., 2009. Catastrophic landslides, glacier behaviour and moraine formation - a view from an active plate margin. *Quaternary Science Reviews*, 28, 1085–1096.

Schrott, L., Götz, J., Geilhausen, M., & Morche, D., 2006. Spatial and temporal variability of sediment transfer and storage in an Alpine basin (Reintal valley, Bavarian Alps, Germany). *Geographica Helvetica*, 61(3), 191-200.

Schurig, C., Smittenberg, R.H., Berger, J. *et al*., 2013. Microbial cell-envelope fragments and the formation of soil organic matter: A case study from a glacier forefield. *Biogeochemistry*, 113(1-3), 595-612.

Small, R.J., 1983. Lateral moraines of Glacier de Tsidjiore Nouve: form, development and implications. *Journal of Glaciology*, 29, 250-259.

Small, R.J., 1987. Moraine sediment budgets. In: Gurnell, A.M., Clark, M.J. (Eds.), *Glacio-fluvial Sediment Transfer: An Alpine Perspective*. Wiley & Sons, Chichester.

Springman, S.M., Jommi, C., Teysseire, P., 2003. Instabilities on moraine slopes induced by loss of suction: A case history. *Geotechnique*, 53(1), 3-10.

Staines, K. E., Carrivick, J. L., Tweed, F. S., Evans, A. J., Russell, A. J., Jóhannesson, T., & Roberts, M., 2015. A multi-dimensional analysis of proglacial landscape change at Sólheimajökull, southern Iceland. *Earth Surface Processes and Landforms*, 40(6), 809-822.

Stoffel, M. and Huggel C., 2012. Effects of climate change on mass movements in mountain environments. *Progress in Physical Geography*, 36, 421–439.

Stoffel, M., Tirantic, D., and Huggel, C., 2014. Climate change impacts on mass movements – Case studies from the European Alps. *Science of the Total Environment*, 493, 1255-1266.

Tonkin, T.N., Midgley, N.G., Graham, D.J., Labadz, J.C., 2017. Internal structure and significance of ice-marginal moraine in the Kebnekaise Mountains, northern Sweden. *Boreas*, 46(2), 199-211.

Vehling, L., Rohn, J., and Moser, M., 2016. Quantification of small magnitude rockfall processes at a proglacial high mountain site, Gepatsch glacier (Tyrol, Austria). *Zeitschrift für Geomorphologie*, Supplementbände Volume 60 Supplementary Issue 1, 93-108.

Warburton, J., 1990. An alpine proglacial fluvial sediment budget. *Geografiska Annaler*. Series A. Physical Geography, 261-272.

Westoby, M.J., Glasser, N.F., Brasington, J., Hambrey, M.J., Quincey, D.J. and Reynolds, J.M., 2014. Modelling outburst floods from moraine-dammed glacial lakes. Earth-Science Reviews, 134, 137-159.

Whalley, W.B., 1975. *Abnormally Steep Slopes on Moraines Constructed by Valley Glaciers*. Proceedings of the Midland Soil Mechanics and Foundation Engineering Society Symposium, Birmingham, pp. 60-66.

Winkler, S., and Matthews, J.A., 2010. Observations on terminal moraine-ridge formation during recent advances of southern Norwegian glaciers. *Geomorphology*, 116(1), 87-106.